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Lubrication

A Technical Publication Devoted to the Selection and Use of Lubricants

THIS ISSUE

Grinding and Polishing as an Adjunct to Lubrication

Thin Oil Film Lubrication

PUBLISHED BY

THE TEXAS COMPANY

TEXACO PETROLEUM PRODUCTS

Surface finish and Lubrication

MACHINERY capable of reproducing its own accuracy of design and construction is indeed unique. It is doubly so where it is essential to the manufacture of those of our daily necessities which must be produced in quantities. This is the status of the grinding machine, as employed by productive industry in the manufacture of accurately designed machine parts.

Effective grinding and uniform polishing of metallic surfaces is very necessary in the application of the required finish to all wearing or frictional elements in order that their subsequent operation with respect to one another can be maintained and rendered most positive by lubrication. There is, therefore, a direct tie-up between surface finish and lubrication.

The grinding machine itself must, of course, be in condition to function efficiently and at the designed speed to bring about this finish. This can only be assured by effective lubrication of its own operating parts. In full appreciation of the high speed conditions which prevail and their effect upon temperature and oil film maintenance, we have, therefore, enlisted the cooperation of our research and refining authorities in an intensive study of the relation of surface finish to lubrication, and the manufacture of lubricants capable of serving equally as well in plant production as in laboratory study.

THE TEXAS COMPANY

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Grinding and Polishing as an Adjunct to Lubrication

PROGRESS in machine design has been responsible for marked interest in the finishing of surfaces of parts which are subject to motion with respect to one another. There used to be a time when shafts or journals were expected to wear in to a running fit with their respective bearings; proper running mesh of gear teeth was also expected to develop over the running-in period. In engine pump or compressor operation, this also applied with respect to piston rings and cylinder walls. During any run-in period, however, any piece of machinery cannot be forced to full power output or production. As a result return on the investment does not really begin until all parts are worn in to a flexible running fit. This, of course, will always hold true to a certain extent. Fortunately, it has been proved practicable to reduce the length of time essential to run-in by giving more thought to surface finish of the respective parts and greater consideration to accuracy in their design and subsequent manufacture. Both can be accomplished by careful grinding and polishing for the purpose of smoothing down those microscopic high spots which would otherwise require flattening in service at the expense of power consumption, loss of productive efficiency and the imposing of an undue load on the lubricant used.

Grinding and polishing of metallic surfaces, as well as various types of solid chemical compounds, is brought about by contact under pressure with some extremely hard material of more or less abrasive nature. Speed is one of the essentials of successful polishing. In consequence the modern grinding machine is designed for extremely high speed operation of its spindle to which the grinding wheel is attached.

By reason of this speed, in studying the lubrication of the various driving elements of the grinding machine, one must consider the potential possibility of an appreciable temperature rise at all points of minimum clearance where the lubricating films will normally be under considerable pressure. Breakdown of the oil film at any such points might readily lead to impaired lubrication and subsequent abrasion of the contact surfaces.

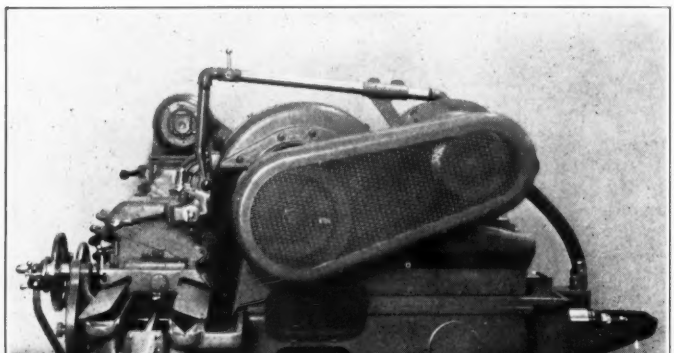
As higher speeds are encountered, lubrication by means of more fluid or lighter viscosity lubricants becomes advisable in the interest of reducing drag, loss of power and increase in film temperatures due to internal friction between the component molecules of the lubricant.

Where speed alone is considered, it will generally be practicable from a lubricating point of view to vary the viscosity or lubricant body inversely with the speed. In other words, for high speed conditions a comparatively light bodied lubricant can be used. Lower speeds will require a heavier product.

It should be understood that the reason for this is that the higher the speed the greater will

be the degree to which the lubricant will be drawn into the clearance spaces by capillary action. The development of a constant film of lubricant within the bearing clearance space, however, will of course be contingent upon the amount of internal friction developed within the body of the lubricant.

In planning for use of grease in connection with high speed grinding machinery, it is well to remember that such products are more particularly adaptable to anti-friction bearing construction. It has been proved that if the bearing is properly designed to retain the lubricant, and a product chosen with a high degree of protective ability, it will insure lubrication for an extensive period of operation, with the necessity for renewal perhaps only three to four times a year.



Courtesy of Norton Company

Fig. 1—Side view of a Norton grinding machine arranged for hydraulic operation of the table and wheel slide. Oil control fittings can be observed through aperture in base.

Any such bearing in service should never be completely filled with lubricant, for this may not only lead to channelling of the product, but also to increased power consumption, due to the drag which may be imposed upon the rolling elements. It may also lead to difficult starting in cold weather.

In connection with gears, chains or other motions, speed must be studied from the viewpoint of the extent to which centrifugal force will be developed and the lubricant thrown from the moving parts. Here there is more relationship between speed and the adhesive characteristics of the lubricant. This will be especially true on exposed gears or chains. For this reason, the designing engineer should study the practicability of using proper housings. In an oil-tight gear or chain housing a comparatively fluid oil can be used, especially if it is automatically delivered to the parts and not merely carried to these by virtue of the dipping of the gear or chain sprockets in the bath of lubricant.

Where gears and chains are not tightly housed, however, thought must be given to the adhesive characteristics as well as the viscosity of the lubricant. It is for this reason that straight mineral petroleum products are more adaptable to such installations than compounds such as greases. Certain types of cylinder stock greases will have comparatively high adhesive tendencies. On the other hand, they will be more expensive and not as resistant to water conditions as the straight mineral residual gear lubricants.

extent to which automatic lubrication is maintained. Obviously if oil is delivered by means of a drip feed oiler, wherein the principle is to supply just enough oil to maintain lubrication, increase in speed, unless the rate of drip of oil is increased, may result in impaired lubrication.

On the other hand where automatic lubrication of the force feed type is involved, there will often be more oil delivered than is required to maintain lubrication. Flood lubrication of this nature will tend materially to resist the effects of pressure. This is of distinct advantage in the grinding machine, where flood lubrication of the high speed elements has been proved to be an adjunct to positive development of speeds as high as 15,000 R.P.M.

There is another advantage to flood lubrication in that the excess oil passing through the bearings will remove a certain amount of the heat developed during operation, or received from an external source. As a result, it may be said that speed leads to the development of a more positive lubricating film, due to the increased capillary action, or the extent to which the oil is drawn into bearing clearances. It also makes possible the use of a lighter product, which will often reduce the amount of power consumed as well as the

OPERATING CONDITIONS OF THE GRINDING MACHINE

The modern grinding machine is built to operate over a wide range of speed conditions, dependent upon the type of work to be performed, the amount of stock to be removed by

grinding, and the nature of the materials involved. By virtue of these speed requirements and the accuracy demanded, the utmost care and attention has been devoted to design and construction of driving mechanisms, wheel spindles, feed screws and wheel slide ways.

Accuracy and rigidity are paramount requirements in any grinding machine intended for mass production service. These features are characteristic of the machine when it is first put into service, being the result of the cooperative efforts of the machine designer and tool builder. The continued maintenance of this accuracy and rigidity, however, is a problem for the operating engineer and lubricating specialist, for lubrication is decidedly essential in effective grinding and the ability to produce the maximum of results with the minimum of power requirement and development of friction.

THE MAIN DRIVE

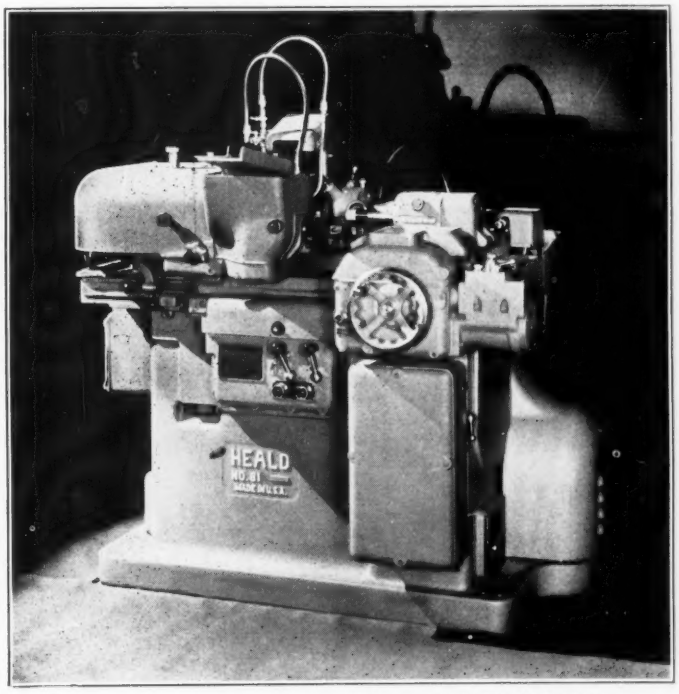
Operation of the grinding machine is brought about by belt connection or an electric motor. The latter permits of greater flexibility in machine operation, reduces vibration and often enables more economical transmission of power. The idler and main drive shaft are very important elements in such machinery. They have, therefore, received careful study relative to the adaptability of the ball or roller bearings as a means of insuring most effective operation. The main drive shaft is, in fact, the salient factor in the maintenance of effective operation of the wheel spindle. On the other hand, this spindle is regarded as the most important member from the viewpoint of lubrication by virtue of its size, the heavy duty to which it is subjected, and the high speeds which frequently prevail.

In machines of the latest type the motor is mounted directly on the wheel slide and connected by Vee belt to the wheel spindle. In such design the motor armature virtually becomes the main shaft.

Principles of Lubrication

Lubrication of anti-friction bearings is but a detail from the viewpoint of the amount of labor and attention involved. The important point is the original selection of the lubricant to be used, and the consideration of its characteristics as required by the principles of anti-friction bearing construction and operation.

In such bearings the purpose of lubrication is to facilitate as easy rolling as possible. To enable this, all the surfaces (which are of a highly polished nature) must be in as perfect condition as practicable. The lubricant must, therefore, serve the dual purpose of lubricating and protecting these surfaces against rusting, corrosion, pitting, or abnormal wear.



Courtesy of The Heald Machine Company

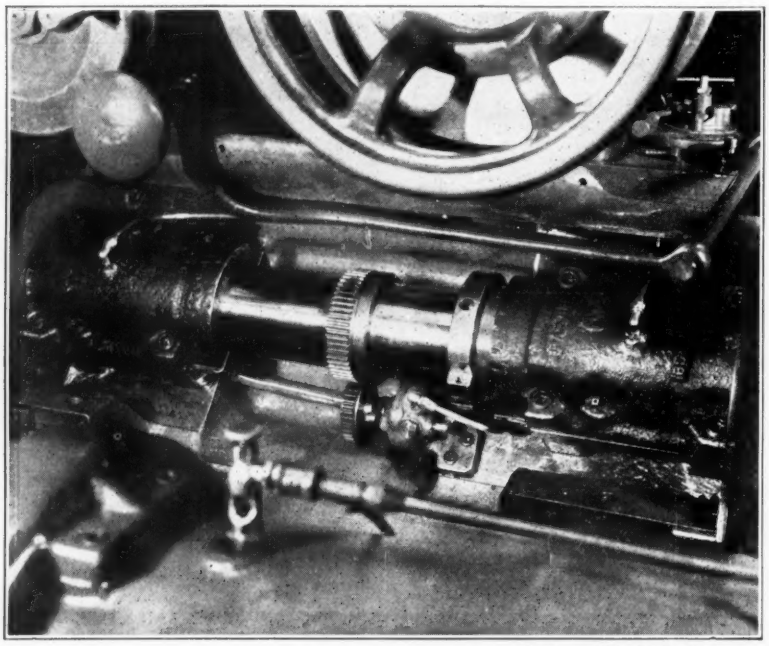
Fig. 2—Showing the Heald Internal Centerless Grinder. On this machine practically all controls are hydraulically operated, including table reciprocation and cross slide feed. Oil lubrication by force feed from an oil reservoir in the lower part of the base insures protection of all wearing parts.

Clearance Requirements and Type of Lubricant

Minimum clearance, of course, is an aid to proper functioning of such bearings, for the occurrence of any play between the component parts would tend to set up a certain amount of pounding which would be detrimental to effective operation. In other words, all motion must be as nearly akin to perfect rolling as possible. Light bodied lubricants should be used wherever they can be successfully retained in such a bearing, commensurate with the temperatures and pressures involved. In the oil seal type of bearing an oil with a viscosity of from 100 to 200 seconds Saybolt at 100 degrees Fahr., is usually most preferable in the interest of reduced torque or power consumption.

Wherever there is a possibility of oil leakage, however, or under conditions of dust, dirt or dampness, it may be advisable to resort to

grease as the lubricant. Greases furnish better seals against the entry of dust, dirt and moisture, thereby serving to protect the polished surfaces of the bearing elements in a very satisfactory manner. Grease also can be very much more effectively retained in a non-oil-tight housing; on the other hand, dirt or grit that finds its way into a grease lubricated bearing has no means of settling out; it will usually be held in suspension, being carried through the bearing elements to act as an abrasive.



Courtesy of Landis Tool Company

Fig. 3—Showing wheel spindle bearings of the Landis Type D hydraulic crankpin grinder; also the lubricating pump.

THE GRINDING MACHINE SPINDLE

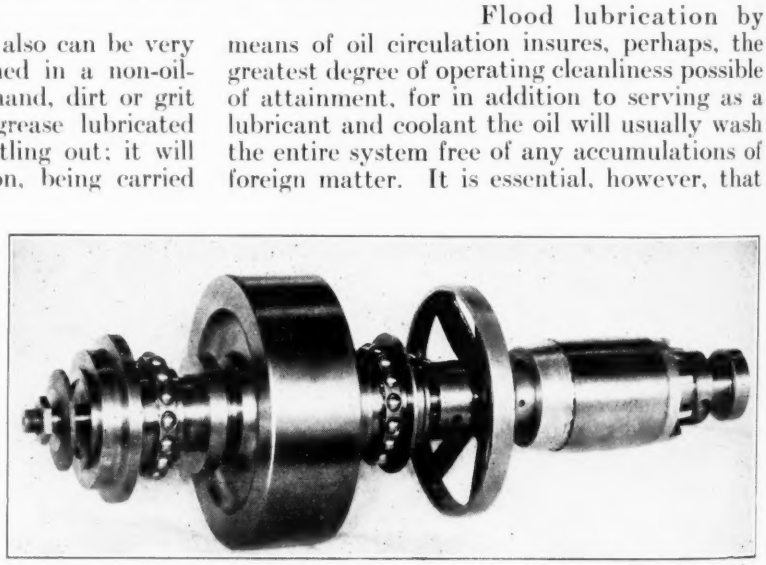
Where the grinding machine wheel spindle is built with plain or so-called sleeve-type bearings, the sight feed oil cup has been proven to afford the requisite degree of lubrication, especially where a wooden oil distributor is properly located within the bearing housing below the spindle. The three-part bearing is extensively used on certain of such machines, viz., a half box is located at the bottom and to the rear of the spindle housing. The top construction consists of two adjustable bearing segments. By means of suitable thumb-screws these latter can be readily adjusted to meet lubrication and pressure requirements without the necessity for stopping the spindle. This permits normal adjustment to be made without interfering with production.

Circulating Oiling Also Practicable

Flood lubrication has also been developed to a marked degree, especially for the preservation of spindles. Mechanical or automatic circulation of the oil to the essential wearing parts can be admirably accomplished by means of a suitable chain driven pump, which is driven from the wheel spindle. There must, of course, be adequate reservoir space with such a system to carry the requisite volume of oil and provide for proper settling. In many machines the hollow wheel slide is used for this purpose; it also serves as a housing for the oil pump.

Cleanliness a Factor

Flood lubrication by means of oil circulation insures, perhaps, the greatest degree of operating cleanliness possible of attainment, for in addition to serving as a lubricant and coolant the oil will usually wash the entire system free of any accumulations of foreign matter. It is essential, however, that there be an ample quantity of oil in the system and sufficient volume in the reservoir to allow for precipitation or settling out of the majority of any foreign matter which may have been taken up during circulation; otherwise, its



Courtesy of Kearney & Trecker Corporation

Fig. 4—Showing three-bearing wheel spindle assembly for the Milwaukee face mill grinder. The grinding wheel spindle is attached directly to the motor armature and the unit rolls on three anti-friction bearings provided for automatic lubrication.

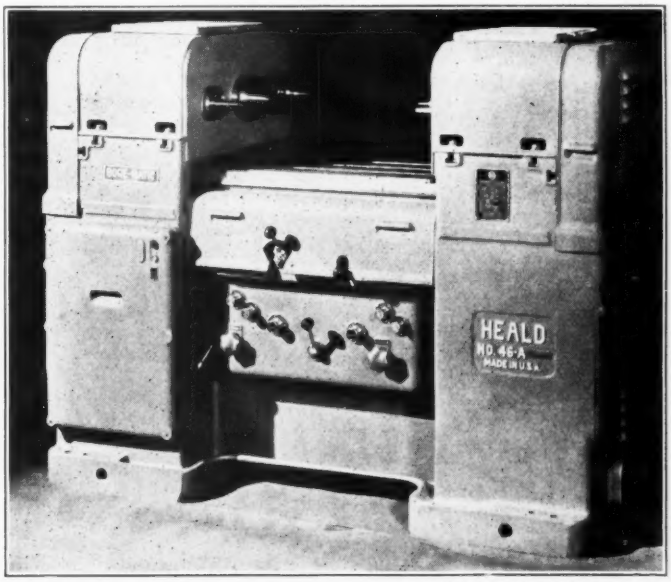
passage through the oiling system may cause serious scoring of bearings and shafting.

Minimum of Attention Required

The minimum of attention is required and normally but little adjustment is necessary in the operation of a flood lubricating system. Relative to adjustment, it is interesting to note that usually a suitable valve can be installed in the bearing cap or at some other accessible point to permit this. On grinding machines, where oil circulation adjustment is provided for in the bearing cap, an observation window or glass located in front of the bearing enables the operator to note the oil flow at all times.

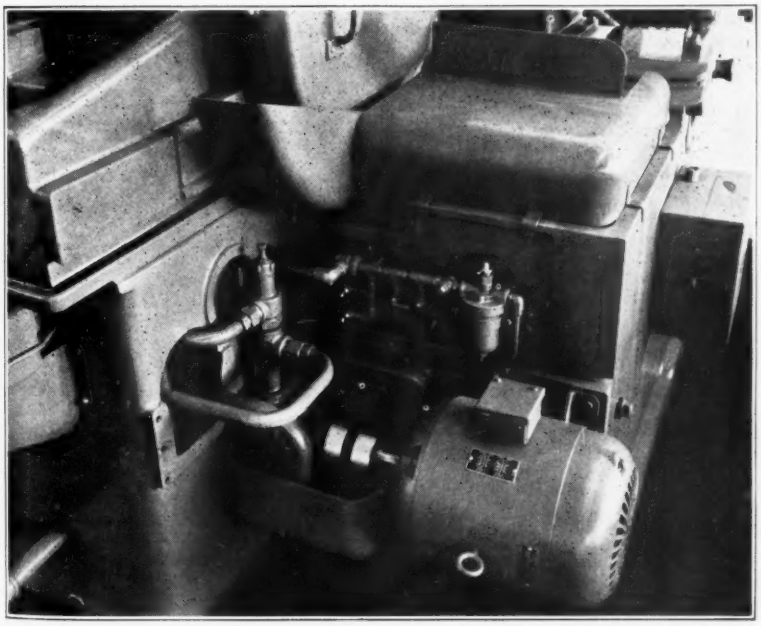
FLUSHING AND CLEANING OF BEARINGS

Maximum protection of any grinding machine lubricant can be assured by keeping the lubricating system as free from foreign matter as is consistently possible, according to the operating conditions and bearing construction. There is always a possibility of entrance of impurities, especially where bearings may not be properly sealed. It is a matter of decided importance, for it can be realized that continued churning of abrasive foreign matter with oil and its passage through plain bearing clearance spaces or in intimate contact with highly polished balls and raceways will ultimately prove the ruination of spindle or main drive bearings and their respective elements.



Courtesy of The Heald Machine Company

Fig. 6—The compactness pertinent to hydraulic operation in machine tool design is exemplified in the above type of Heald machine.



Courtesy of Norton Company

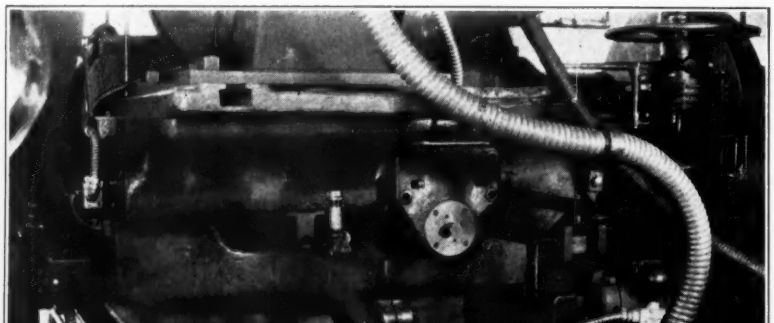
Fig. 5—Showing piping and valve arrangement for lubrication of the wheel slide and base ways of a Norton grinding machine. Oil is pumped from a main reservoir within the base, through a filter and thence to the parts to be lubricated.

In view of the fact that it is not always possible to effect the requisite degree of sealing or to depend upon the seal being in good working order at all times, grinding machine bearing lubricating systems should be flushed and cleaned at periodic intervals. The frequency will, of course, depend upon the design of the bearing, the type of seal, the lubricant used and the extent to which dust and dirt are present.

Flushing Dependent on Type of Bearing and Means of Lubrication

Systems served by sight feed oilers will in general require more frequent attention than ball bearings, due to the fact that their housings may be less carefully designed. Cleaning of drip-oiled plain bearings may be necessary or advisable at periods ranging from every two weeks to every several months. With ball or roller bearings once or twice a year is sufficient, unless operating conditions are especially dirty.

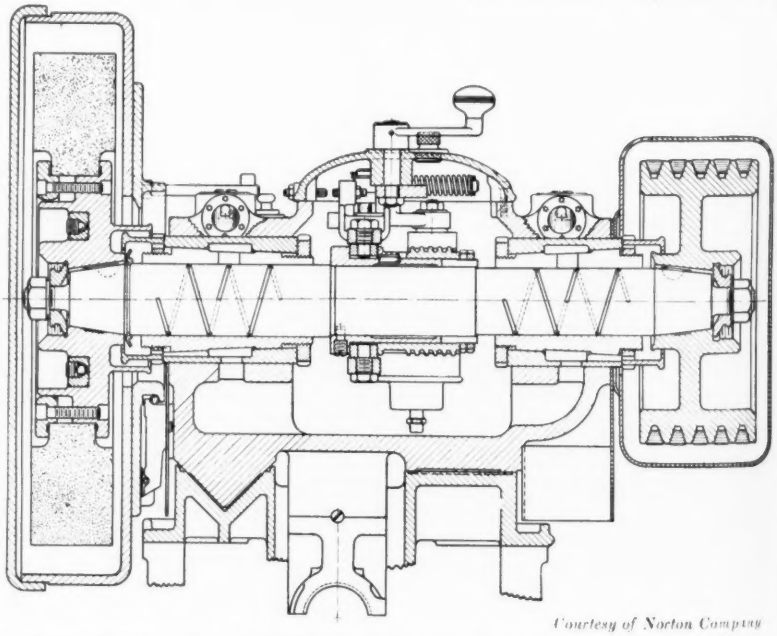
Anti-friction bearings, however, are more delicate from the viewpoint of construction, and therefore the lubricant should not be allowed to become as contaminated as is permissible with other types of bearings.



Courtesy of Landis Tool Company

Fig. 7—Another view of the Landis Type D crankpin grinder showing wheel carriage guideway and other parts. Oil is pumped under pressure through a suitable oil filter prior to delivery to the parts to be lubricated.

Circulating oiling systems, in turn, possess natural advantages in that the flood of oil which is constantly passing through the bearings tends to wash out any grit, dirt, dust or metallic particles that may have gained entry. As a result, wear is reduced to a minimum, just as long as the oil in the system does not become so highly contaminated as to be unable to precipitate such foreign matter during its period of so-called rest. For this reason the condition of the oil should be carefully watched and the system drained as soon as any excess of dirt becomes apparent in the reservoir or settling chamber.



Courtesy of Norton Company

Fig. 8—Showing grinding wheel slide construction common to many types of Norton machines. The bottom of the wheel slide casting serves as an oil reservoir from which oil is pumped through a filter to pipes shown in the bull's eyes, from whence it flows by gravity to the wheel spindle bearings via suitable oil grooves.

SELECTION OF LUBRICANTS

Spindles

Normal conditions of grinding machine spindle operation will permit the use of a light to medium bodied straight mineral spindle or machine oil, the degree of refinement depending to a large extent upon the type of lubricating system.

In sight feed oilers, as used for spindle lubrication on many machines, an oil of from approximately 100 to 200 seconds Saybolt at 100 degrees Fahr., will adequately fill the clearance spaces and prevent abnormal vibration should these latter be comparatively high. Relative to the rate of oil feed, it is interesting to note that some authorities recommend adjustment of sight feed oilers to deliver from about 7 to 10 drops a minute.

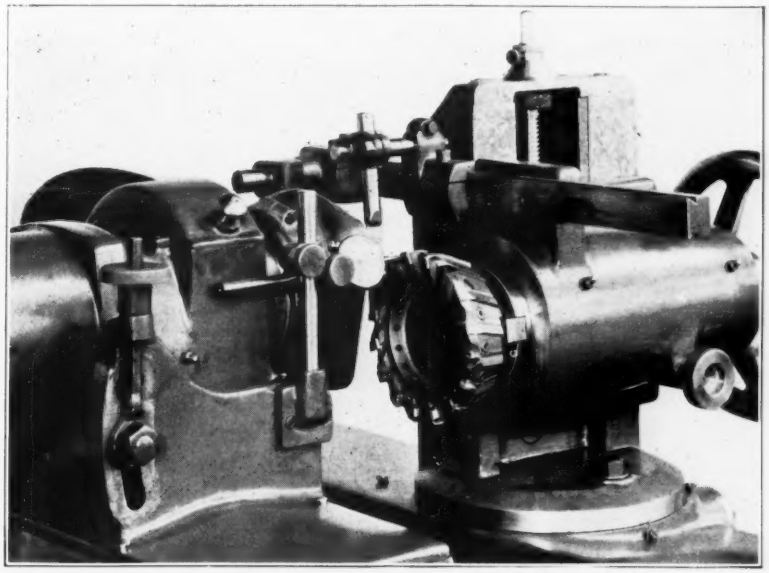
It is practicable to use this same grade of oil for the spring-actuated wick-oiled bearing. In the ring oiling device, however, a somewhat heavier product will be necessary, the viscosity ranging from 200 to 300 seconds.

Circulating Systems

Grinding machine bearings served by cir-

culating systems can normally function on an oil of similar viscosity as mentioned for the spindle bearings. Re-usage of oil by circulation, however, imposes a very important requirement upon any oil for such service. In other words, it must readily separate from water or other foreign matter, and not tend to develop emulsions to any extensive degree.

For this reason attention must be paid to the degree of refinement of any oil under consideration. That is, an oil should be used which has been so refined as to remove those hydro-carbon constituents which may lead to subsequent emulsification, especially when the oil is agitated in the presence of air, and perhaps in contact with water or particles of metallic foreign matter. As a rule a viscosity range of from 100 to 300 seconds Saybolt at 100 degrees Fahr., will meet requirements.



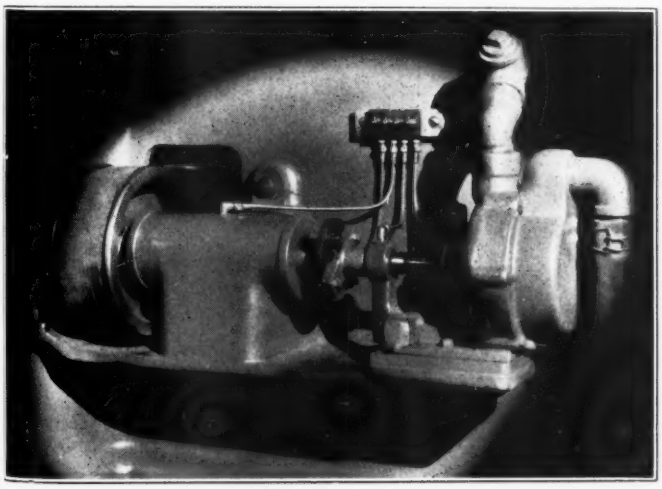
Courtesy of Kearney & Trecker Corporation

Fig. 10—Cutter and wheel spindle supports on the Milwaukee face mill grinder. Cutter spindle is mounted in a Timken roller bearing. The flat bearing surfaces on this machine are lubricated by a wick fed from oil cups.

Gear Shaft Bearings, etc.

For those other wearing elements in the average grinding machine, including reversing mechanisms with their essential gears, cams and bearings, an oil should be used which will meet the requirements of both hand and bath lubrication. This latter is prevalent in many reversing mechanism housings. The oil cup, however, prevails on the majority of the other general machine bearings.

The duty involved is not severe. Therefore, a medium bodied straight mineral machine oil will, as a rule, serve the purpose satisfactorily, the viscosity range being from 200 to 400 seconds Saybolt at 100 degrees Fahr.



Courtesy of Norton Company

Fig. 9—Showing grease gun fittings for a Norton shaft bearing and pump drive unit.

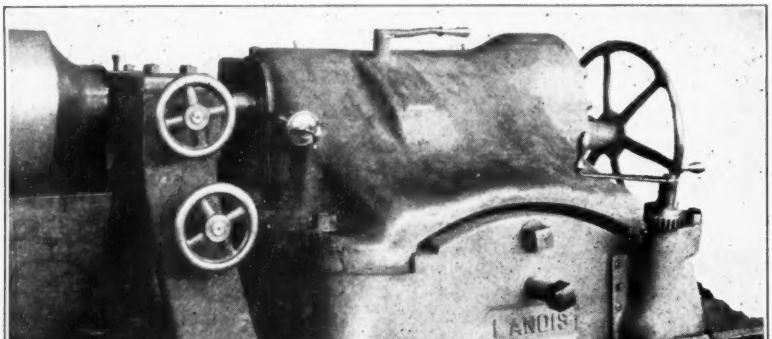
Flat Bearing Surfaces

There may, however, frequently be a problem in the lubrication of flat bearing surfaces such as V's and table ways, due to the varied pressures which may be developed. For this reason the utmost care should be paid to selection of the oil to be used, and the extent of viscosity or body required.

Lubrication of such surfaces can be accomplished by oil cups and suitable grooving of the ways, by application of the oil under pressure as in a force feed system or by the installation of rollers located in depressions which can be kept full of oil. These latter are more automatic, for at each passage of the slide the respective rollers carry a film of oil up to the surfaces of contact, in much the same manner as a ring-oiler would lubricate a plain bearing.

The viscosity range to meet the pressure conditions of slide operation must of necessity be wide. Oftentimes, on smaller grinding machines it can be as low as 300 seconds Say-

bolt at 100 degrees Fahr. On the other hand, larger machines such as those designed for the grinding of steel mill rolls may require a lubricant as heavy in body as a steam cylinder oil, the actual viscosity being perhaps as high as 130 seconds Saybolt at 210 degrees Fahr.



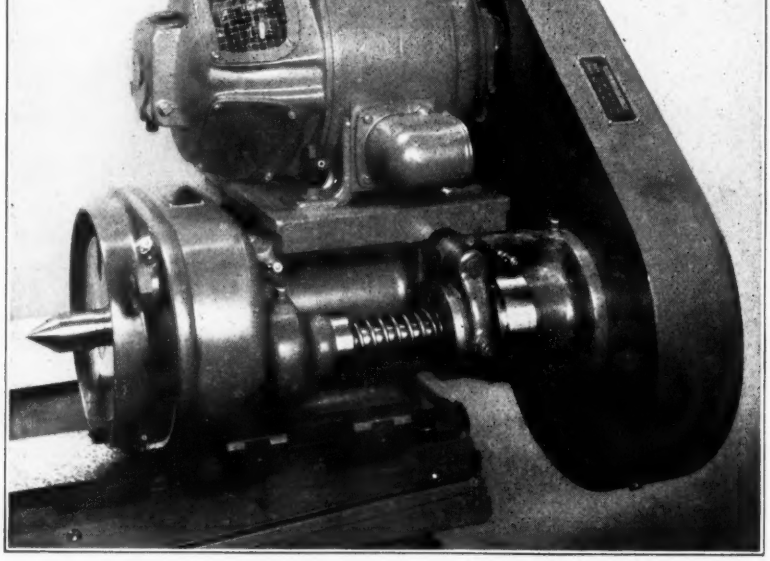
Courtesy of Landis Tool Company

Fig. 11—Showing how the footstock center of the Landis Type 30 roll grinder is lubricated by means of a grease cup.

CONCLUSION

The selection of lubricants for grinding and polishing machinery has in the past been very often a more or less haphazard matter, depending upon the experience of the machine operator, and his ability to estimate pressures and note the extent to which wear may take place. In this regard, however, it is well to state that the lubricating engineer has been instrumental in bringing about a decided change for the better in many plants. He can very often be of considerable service by virtue of his experience over a wide variety of operating conditions.

Lubricating engineering service is one of the greatest assets in the operation of mass production machinery. To the operator it affords an especially economical way of availing himself of expert technical advice in the solution of lubrication problems, and the selection of lubricants capable of maintaining operation most economically and effectively. Under conditions of comparatively high speed, such as prevail in the average grinding machine, knowledge of lubricating ability is highly essential for the most efficient performance, for the modern grinding machine has passed beyond the stage of guess-work in regard to lubrication. One must be positive that lubricants are capable of affording maximum protection of all moving parts, for as speeds increase very often boundary lubrication is approached.



Courtesy of Norton Company

Fig. 12—Showing pressure grease fittings on a live spindle headstock of a Norton machine through which grease is applied to main bearings.

THIN OIL FILM LUBRICATION

In the concluding paragraph of the previous article of this series,* an important distinction between boundary film, and fluid film lubrication, was pointed out. In the former, the oil film is only a few molecules thick, and in order to produce slip of one surface over the other, it is necessary to apply a measurable force. In fluid film lubrication on the other hand, where the layer of oil is thick, one metal surface can be moved relatively to the other by applying an indefinitely small force.

It is now necessary to consider the question of boundary friction in greater detail, and to see how it applies to the practical problem of lubrication.

In order to reduce the problem to its essential elements, let us set up an ideal system of metal surfaces separated by a layer of oil. Imagine two similar cylindrical metal discs with absolutely flat surfaces, suspended on wires, and completely immersed in a bath of oil. Bring the flat faces very close together so that they are separated by a layer of oil of "fluid film" dimensions.

It is probable that the minimum distance of separation of the two metal faces for this result to be obtained, is in the neighborhood of 1/10,000 inch, which is equivalent to the combined thickness of many hundred layers of oil molecules.

Let us look a little more closely at the layer of oil between the two discs. In the interior of the film of oil, the molecules are free to wander about, as they do in any liquid. Their movements are quite random, and are due solely to the effects of temperature. If one surface be moved across the face of the other, a drag will be felt, just as a drag is felt when an oar is moved through the water. This is fluid friction, and depends on the viscosity of the oil. The important thing to notice is that the force required is proportional to the speed of movement of one disc over the other. At an indefinitely low speed, the force is indefinitely small. In other words, there is no static friction at all, but only viscous friction.

Suppose now that the mechanical design of our pendulum supports is so delicately precise that we can gradually reduce the distance apart of the two metal faces, to any required figure. It will of course take a very long time for the free oil between the opposed surfaces to seep out, when the film gets very thin. Efflux of free oil from between the discs into the bath surrounding them will not, however, continue indefinitely, and probably not beyond the stage when the film is less than 10 molecules thick. We are now entering the "boundary film" region where new effects are noticeable. The principal difference we find is that it is not possible to start one surface moving over the other until a certain definite force is applied, or in more usual language there is now a measurable coefficient of static friction.

When we enquire into the reason for this change in behavior we learn that it is due to the fact that the molecules in this very thin film are no longer free to move about at random but are tied in some way to the metal surfaces. When an attempt is made to dislodge them, they resist the disturbing force, and no slip of one surface over the other can take place without the expenditure of work.

A further phenomenon which is observable when working in this boundary film region is the variation of the coefficient of static friction with variations in the type of molecules constituting the boundary layer. It has been very clearly established by the work of Hardy, Langmuir, N. K. Adams, Paul Woog, and others, that there exist several factors which are responsible for the special phenomena grouped under the term "Oiliness."

OILINESS

It must be pointed out that oiliness is not an intrinsic property of the oil itself. It is rather a property of the interface between oil, and its partner, metal. The character of the opposed metals, and the molecular type of the oil film between them, both play a part in influencing the value of the resistance to traction, or in other words, the coefficient of static friction.

Perhaps the factor of chief interest in the study of the problem of oiliness is that the oil molecules arrange themselves in a definite direction when very close to, or in contact with, a metal surface. The term "orientation" is applied to this tendency, and is a term of quite general application. For example, a compass needle is oriented North and South, due to the fact that the earth has a magnetic field. Iron filings orient themselves when brought close to, or in contact with, a magnet. A small, sausage-shaped conductor, suspended by a silk thread and brought near an electrically charged metal plate will orient or set itself with its long axis pointing to the exciting charge.

All molecules, whether gaseous, liquid, or solid, may be regarded as built up of electrical charges, positive and negative charges being present in equal amounts, thus making the molecules as a whole, electrically neutral. However, in many types of molecule, these positive and negative charges are not symmetri-

* See Lubrication, August, 1934, pp. 93

cally distributed, with the result that the molecule behaves as if it had an excess pair of positive and negative charges nearer one end than the other. An analogy will perhaps make this clearer. Suppose we build up a short cylinder out of glass marbles and corks, cemented closely together in a perfectly regular manner, there being such a proportion of marbles and corks that the body as a whole has a specific gravity equal to unity. If immersed in water it would float just below the surface and would remain in any position chosen. It has no apparent weight and has no gravitational orientation. Now suppose the same marbles and corks are cemented together into the same cylindrical form but that the arrangement is not regular, there being a larger proportion of corks towards one end and of marbles towards the other. Immersed in water, the cylinder would, as before, float just below the surface, but now it will not take up any random position. The lighter end will be higher than the heavier end, or in other words, it is gravitationally oriented.

Returning now to our problem of what is happening in the boundary film of oil on a metal surface. The problem will, at this stage, be a little simpler if we suppose the boundary film to be composed entirely of molecules of a fatty oil, or a fatty acid such as oleic acid. This molecule, according to Langmuir, is shaped like a short cylinder, the ratio of length to diameter being about 2 to 1. The chemist tells us that the main body of the molecule consists of hydrocarbon groups, but that at one end there is a group containing oxygen and known as the "carboxyl group." Finally, the physicist tells us that it is in this carboxyl head that the unbalanced electrical charge exists. It is, in a manner of speaking, the active end of the molecule, and any explanation of the behavior of the oleic acid molecules in the boundary film must be referred to the activity of the carboxyl group at one end of the molecule.

Now let us transfer our attention for a moment to the metal surface. It is rather startling to be told that a surface is "active." The phenomenon of surface tension is familiar to everybody. Take a dry camel hair brush. The hairs are all separated. Dip it bodily into a glass of water. Again, we see that the hairs are all separated. Now take it out, and we see that the hairs are all drawn closely together. Obviously it is not the fact of dryness or wetness that is responsible for this behavior, and yet, water is in some way connected with the phenomenon. A little thought will show us that the only difference between the wet hairs in the water and the wet hairs out of the water is that in the latter case they are enveloped in a drop of water having a *free surface*. There is a force, or tension, which draws the surface into the smallest possible compass. Small globules of mercury scattered on a table are spherical, because a sphere has the smallest possible surface for a given volume. Surface tension is a manifestation of the free energy of a surface, and every surface, whatever its nature, exhibits this in greater or less degree.

The physicist, probing as he does into the root causes of the phenomena he observes, finds that, in the last analysis, the surface field is electrical in nature. Not that the surface of a piece of metal is electrified in the usual sense, but that the molecules immediately at the surface behave as if they carried minute electrical charges. The general effect is of an electrical field of force extending out from the surface an exceedingly small distance and only affecting material brought within its range, which means that anything to be acted upon by this free field of force must be extremely close to the surface.

We can now see what will happen in a boundary film of oleic acid on a metal surface. The molecules will turn their active ends inwards towards the metal, and those in the bottom layer will be attracted very strongly to the metal forming what is called an "adsorbed layer." Those in the next layer will try to squeeze themselves into any vacant spaces between the molecules in the layer beneath, and so on through several layers. A few layers out from the surface the orienting force has fallen off to nothing, the molecules are lying at random, and we are on the outer edge of the boundary layer. The total thickness of the boundary layer will vary with the activity of the molecule and with the activity of the surface field of the metal, and this goes far in explaining why we find varying degrees of oiliness with different combinations of metal and oil.

Another factor which plays a great part in the phenomenon of oiliness is the influence of the molecular dimensions of the molecules of the lubricant. It is much more difficult to displace large molecules from their average positions of stability than it is to displace small ones. A mechanical analogy due to one worker on this phase of the problem, employs the picture of three heaps, respectively of sand, of stones, and of cannon balls, to represent small, medium and large molecules. A rod can be easily thrust into the heap of sand, with great difficulty and not very far, into the heap of stones, and not at all into the heap of cannon balls.

The work of Hardy is important as showing the influence of molecular weight on coefficient of static friction. Fig. 1 is a composite diagram

from his paper: Boundary Lubrication—The Paraffin Series,* and is interesting as showing a straight line relation between coefficient of static friction and molecular weight for a number of members of the paraffin series and also for their related alcohols.

With these considerations in mind, we are able to form a more or less true conception of the mechanism of oiliness.

Returning for a moment to our ideal system of two absolutely flat metal surfaces separated by a film of oil of boundary film dimensions,

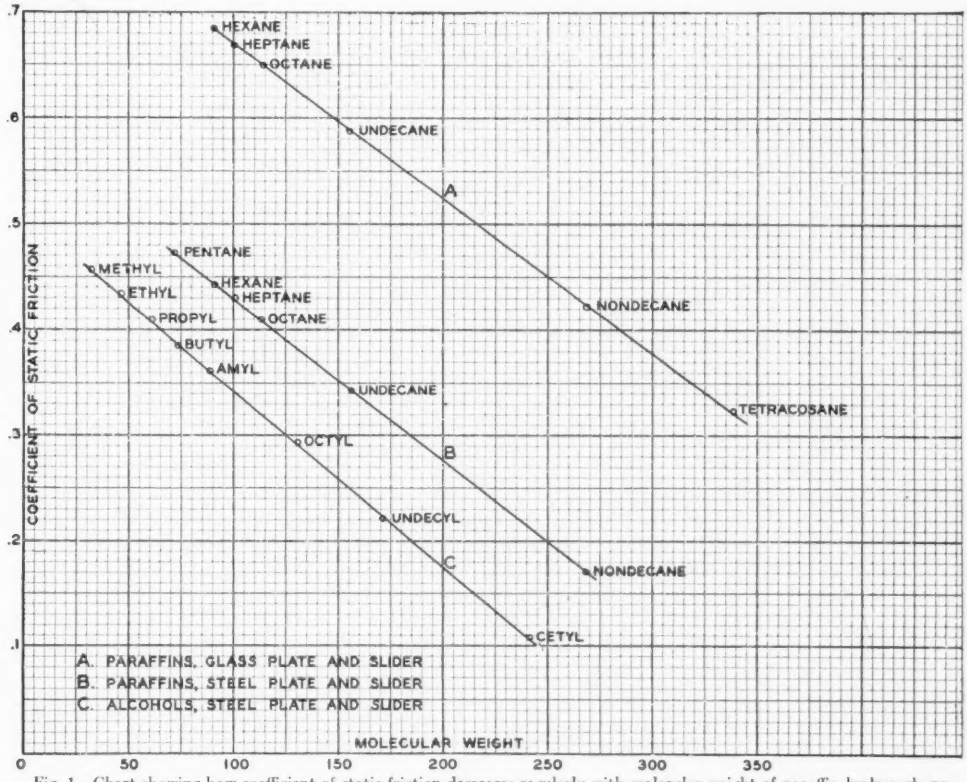


Fig. 1—Chart showing how coefficient of static friction decreases regularly with molecular weight of paraffin hydrocarbons. —*From Hardy & Doubleday**.

A point of very great interest which is at once obvious from the graphs, is that the lines if continued would cut the molecular weight axis at zero friction. As a matter of experimental fact, however, Hardy found that it was not possible to observe this point owing to experimental difficulties, and lack of sensitivity of the apparatus.

The influence of the surface field of the solid phase is clearly seen, the frictional coefficients for the same material being different for glass and steel.

The fact that the graphs are parallel is explained by Hardy on the ground that the effect on friction of each molecule of the lubricant is independent of the nature of the solid surface and depends solely on how the molecule is built up. This latter point is confirmed by a comparison of the graphs for the paraffins and their related alcohols. The latter, having electrically active portions, give lower coefficients of friction. The graphs, however, remain approximately parallel to those of the paraffin graphs.

* Hardy & Doubleday. Proc. Roy. Soc. 100-A (1922).

the first question for consideration is—what is the maximum thickness which a film may have and still be described as a boundary film? Since the outstanding property of such a film is that of stability, we must push the enquiry back a little further and ask to what is the stability of a boundary film due? Stability in an oil film separating two metal surfaces means resistance to removal of oil by pressure applied between the surfaces. When the boundary film is reached, all free oil has seeped out, and what is left is bound to the surfaces by electrical forces. The oil which thus remains behind, adsorbed by the solid surface, is itself, virtually a solid, having lost its mobility, which is the distinguishing property of a fluid.

We have then, a solid film of lubricant comprising a number of molecular layers, and we now want to know something about the causes which may modify the thickness of this film. Although the electrical field of a clean surface extends outward only a very small distance, in Hardy's words, "The solids may be supposed to modify cohesion right through a layer of lu-

bricant, by spreading of strain in this way, even though the absolute range of their attraction may be as small as Langmuir supposes it to be."

The more active the molecules comprising the adsorbed layer, the greater the number of elementary molecular layers we may expect to be affected by this spreading of strain. It is more difficult to form a satisfactory picture of the structure, behavior, and limiting thickness of a boundary film composed of non-acting molecules such as the paraffin series of hydrocarbons. Examples of light members of this series are: Hexane, Heptane, and Octane, which contain 6, 7 and 8 carbon atoms in the molecule, respectively, combined in a perfectly symmetrical manner with 14, 16, and 18 atoms of hydrogen, in a chain formation. An example of a much heavier and longer molecule is tetradecane, which contains 14 carbon atoms and 30 hydrogen atoms. It is a liquid at room temperature, but solidifies at about 42 degrees Fahr. Molecules of this type behave very differently from an oleic acid molecule, and this difference of behavior is due principally to the fact that in the paraffin molecule the distribution of electrical charge is perfectly symmetrical, whereas, as we have seen, in the oleic acid molecule, there is an unbalanced electrical moment situated at one end.

A molecule, however, although it may not possess a permanent electrical moment, may have its internal electrical symmetry thrown out of balance by the inductive effect of an external field.

A simple electrical experiment, already referred to, may throw light on the problem. Suppose we suspend a small cylinder of some conducting material by means of a torsionless fibre attached to the middle of its length. There being no directing moment whatever, the cylinder will of course remain in any position in which it may be placed. Now bring up near it a metal plate carrying an electrical charge. The suspended conductor will turn so that its long axis points towards the plate, and if the latter is brought near enough, the cylinder will attach itself by one end, to the surface. The choice as to which end sticks to the plate is simply a question as to which end happens to be nearer the exciting charge at the outset.

The explanation for the described behavior is of course well understood. There is, in any insulated conductor brought into an electrical field, a separation of charge by induction. On the end nearer to the exciting charge, the polarity will be of opposite sign, and on the far end, of the same sign. In other words, a temporary electric moment has been given to the originally neutral body.

We can now reduce this large scale behavior to molecular dimensions, and enquire what will happen if a paraffin such as hexane is brought into contact with a metal surface.

At a short distance from the surface, the molecules have perfectly random movements, and no orientation whatever. Those in contact, and very close to the surface, will, by virtue of their temporary induced moment, orientate themselves vertically to the surface, forming an adsorbed layer. The free field of the metal will not be saturated by a monomolecular layer, but it is unlikely that a stable film of as many layers as is possible with polar molecules will be built up. In other words, if we press two metal faces together having a non-active body, such as a paraffin, between them, we shall be able to squeeze out more free molecules than if the material were, say, a fatty acid. Let us ask a definite question: What would be the effect on the coefficient of static friction between two flat steel surfaces separated by (1) a boundary film of hexane, or (2) tetradecane? The answer to this question is based on our assumption that the number of molecular layers in the true boundary film will be about the same for the various members of the same family group, and therefore that the thickness of the boundary film will be some function of the length of the molecule. This view suggests a possible explanation of the experimental observation made by Hardy, already referred to, that the coefficient of friction decreases regularly with increasing molecular weight. With heavy members of the paraffin series, the opposed metal surfaces are further away from each other than if low molecular weight members composed the boundary film. It is the opinion of many investigators that an important factor which influences friction of metal surfaces separated only by a few molecular thicknesses, is the mutual interaction of the free surface fields. This interaction will be greater the closer the surfaces approach, which satisfies the experimental observation.

It will of course be understood that while such low molecular weight bodies as the first members of the paraffin series or of their related alcohols, are, in a sense, lubricants, they would have no value whatever in practical service. In the first place, they give very high coefficients of static friction, and, what is more serious, entire failure of lubrication would occur at very low working loads.

This last statement leads us directly to the problem of what happens at metal surfaces in contact, when lubrication is entirely absent, or in other words, when they are in "clean" contact. This is a very important phase of the general problem of thin oil film lubrication and will be taken up in the next article.

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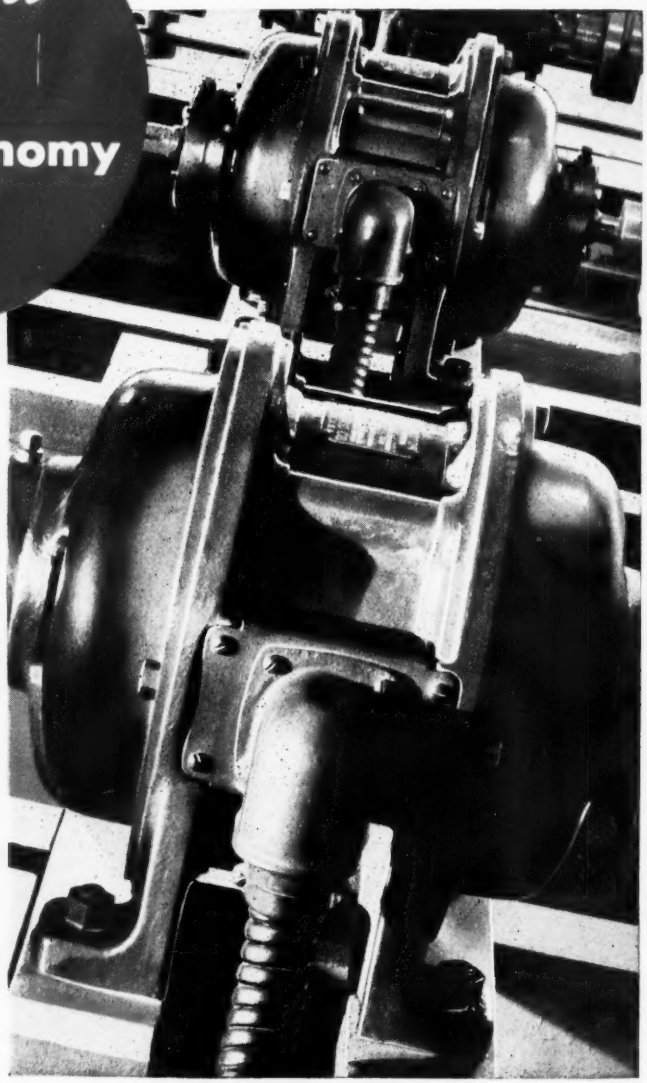

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